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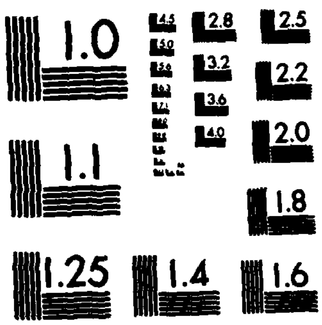

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PREVENTATIVE MEASURES TO LIMIT STRESS CORROSION CRACKING IN PRESTRESSED CONCRETE

by

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In the past decade, the most significant advances in the area of protection of prestressing steel from stress corrosion cracking have come in the fields of metallurgy and concrete materials. These efforts have developed from a more precise understanding of the mechanisms that cause stress corrosion cracking in prestressing steel, and development of concreting materials that provide greater protection for these steels. This report deals with two

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aspects of steel protection. First, with respect to the steel itself, new insights into the structure of the prestressing steels have shown metallurgists the conditions under which stress cracks form and advance, as well as ways in which to modify the physical properties of the steel to minimize the possibility of crack formation and advancement. Secondly, in the field of concrete materials, the emphasis on prevention of corrosion to steel has been in the area of durability of the concrete that protects the steel. Lower water-cement ratios and concretes with lower permeability exclude deleterious materials from the surface of the steel. New materials and procedures are discussed that have been designed to limit the penetration of corrosive elements that may attack the steel at the grain boundaries and initiate brittle failure.

Preface

This paper was prepared for presentation at the Third Symposium on Stress Corrosion of Prestressing Steel, sponsored by the Fédération Internationale de la Précontrainte, which was held 22-23 September 1981 in Madrid, Spain.

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Commander and Director of the WES during publication of this report was COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

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PREVENTATIVE MEASURES TO LIMIT STRESS CORROSION CRACKING IN PRESTRESSED CONCRETE

Introduction

1. Probably the least fully understood area of corrosion to metals is that of stress corrosion. It is not a simple phenomenon, caused by one unique, well known chemical or electrochemical reaction occurring under a single type of environmental condition. Rather, it can attack a wide range of metallic materials under a large number of environmental conditions and is subject to many unknowns with respect to degree of predictability of damage. Yet for all that is unknown about its occurrence, it is not a condition that must be feared, or one that cannot be controlled or prevented. What has been learned about this phenomenon deals with engineering properties of the materials affected by stress corrosion and methods that can be taken to insure that failure from this condition can be prevented. What has been learned with respect to its prevention is probably more in the realm of common sense and good engineering design judgment than that of extraordinary material engineering breakthroughs. Nonetheless, the methods are reliable and achievable in most cases without undue expense or procedural difficulty.

2. Stress corrosion cracking (SCC) occurs in many different metals under many different conditions. This report deals with the aspects of the problem applied to prestressing steels. That in itself does not narrow the range of occurrence of the problem significantly, but it does allow concentration on solutions which are applicable to prestressing steels, and in most cases allows for protection of the steel in the alkaline environment of concrete or grout. Many fine papers have been written which deal in detail with the causes of SCC. For this reason, this discussion is directed toward methods of minimizing the chances of such an occurrence. Many advances have been made in understanding the way in which stress corrosion attacks steel. If these conditions are understood, steels can be chosen to suit the situation or modified to prevent SCC. In addition, the concrete that generally surrounds the prestressing steel is a material that can have many different properties depending upon its composition. If its composition is adjusted, the properties of the concrete can be developed to produce a highly protective

environment which will prevent the flow of gases and liquids from reaching the level of the embedded steel.

3. For stress corrosion to occur, two conditions must be met. First, the metal that is subject to SCC must be in contact with a corrosive environment, such as carbon steel in a chloride or nitrate environment. Second, the metal must be under some form of stress. Both conditions are necessary. If the steel is under stress and not subjected to the corrosive environment, it is very likely that it will remain ductile and the brittle condition associated with SCC will not occur.

4. There are two types of stress corrosion. The anodic type, which takes place at the site of the anode in a corrosive situation, occurs in many different types of metals and each metal requires a specific active agent which produces the stress crack. The cathodic type occurs at the cathode and is most generally considered to be associated with hydrogen embrittlement because of the release of hydrogen at the cathodic site. This hydrogen is generated at the cathode as a result of loss of metal at the anodic site. At one time, hydrogen embrittlement was considered separately from stress corrosion cracking. But since it is caused by absorption of hydrogen ions into the structure of the steel, and it only occurs under the conditions of stress to the metal, it has recently been considered a form of SCC.

5. In order to prevent SCC, the presence of the corrosive environment must be removed from the surface of the prestressing steel, the prestressing steel must be modified such that the environment is not harmful to it, or the tensile stress condition must be removed from the steel. Since it would be counterproductive to remove the tensile stress from the steel, it remains that, to minimize the possibility of SCC, the surrounding environment or the properties of the steel must be modified to the point where conditions are not conducive to cracking of the steel.

Preventative Measures that Can Be Taken to Modify the Properties of the Steel

6. The two major categories of prestressing steel are (a) cold-drawn and (b) quenched and tempered. In the cold-drawing process, wire is pulled through a series of dies, each of successively smaller diameter, until the wire is reshaped to the proper diameter. This process deforms the crystalline structure of the steel, making the crystals longer in the direction of drawing

as compared to the direction perpendicular to the direction of drawing. A crystalline orientation is produced that is somewhat like that shown in Figure 1. The elongated crystals tend to align in the direction of drawing,

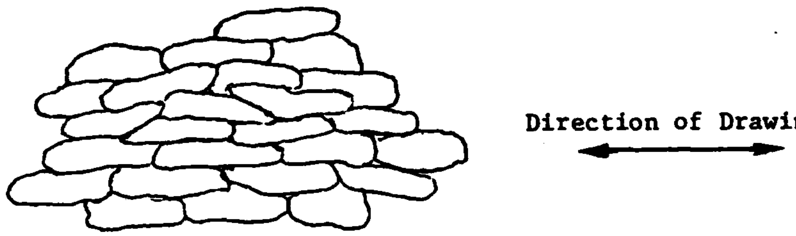


Figure 1. Sketch of grains showing elongation produced by wire drawing process

which is also the direction of stressing. The crystal (or grain) boundaries that are oriented perpendicular to the direction of drawing do not align. This effect does two things. First, the path that an intercrystalline stress corrosion crack would have to take is much longer than if the steel had not been cold drawn. As the crack penetrates from the surface, it hits the boundary of an elongated crystal and must travel along that boundary in the direction of the elongated length before being able to continue on an inward course. Thus, the drawing process makes it harder for cracking to penetrate the steel structure. Second, stress corrosion cracks found in drawn wire tend to be oriented perpendicular to the direction of drawing on the surface of the wire, but as the crack progresses into the steel structure their orientation tends more toward the direction of drawing, since the alignment of crystal boundaries is more favorable for crack extension in the direction of drawing than perpendicular to it. In an SCC situation where crack propagation can be directed parallel to the direction of stress rather than perpendicular to it, wire failure can be prolonged or in some circumstances prevented.

7. Cold-drawn wires are almost always stress relieved today. The process of drawing the wire builds up internal stresses that contribute to lowering the ultimate tensile stress of the steel. However, if the steel is heat treated for a period of time, these stresses are relieved, and the steel can withstand greater external stress and will have higher ultimate strength. The properties changed by heat treating to relieve internal stress are the ultimate strength and the elongation properties. The temperature that produces an

optimum proof stress (200 to 225°C) also provides a pessimum elongated percentage (a ductility factor that is very important with regards to SCC) and a tendency to be notch sensitive in certain corrosive atmospheres. If the stress relieving temperature is increased to the range of 300 to 400°C (Netherlands Committee for Concrete Research 1971) as shown in Figure 2, a compromise of lower proof stress and higher elongated percentage is achieved which produces a more SCC-resistant, cold-drawn, stress-relieved prestressing wire.

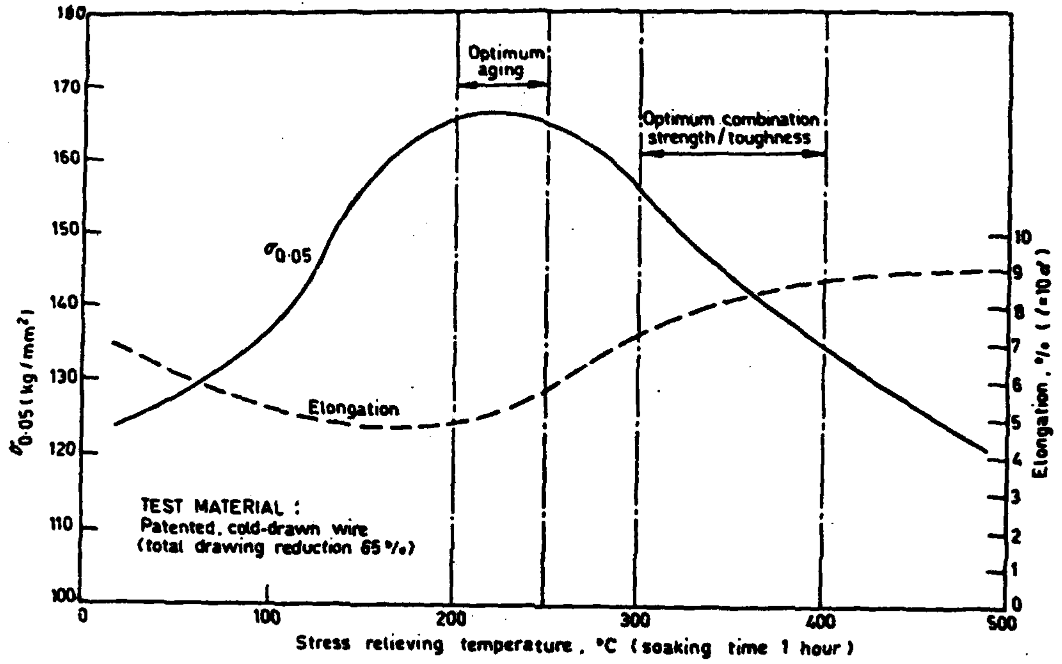


Figure 2. Influence of stress relieving on the properties of prestressing steel

8. Quenched and tempered wire, on the other hand, is wire that has not had its crystalline structure altered by drawing. Its structure contains more rounded crystals with no particular grain boundary orientation. Its strength is obtained by heating rolled wire to 800 to 900°C and then quenching in oil. This process produces a hard, brittle structure. To remove its brittle properties, the steel is further treated by tempering to between 400 to 500°C. With respect to SCC, cold-drawn wire is preferred to that produced by quenching and tempering because of the structure orientation produced by the drawing process. The newer methods of quenching and tempering have produced steel that is quite resistant to SCC, whereas with the old methods, quenching and tempering was greatly inferior to cold-drawing for stress-corrosion resistance.

9. Another method of inhibiting crack formation by changing the properties of the steel has been pointed out by Brachet (1977). Decarbonizing the surface of the prestressing steel uniformly to a significant depth produces a steel that when tested under hydrogen embrittlement conditions causes brittle failures, but the initial location of the brittle cracks are in the center of the steel wires, away from the surface that had been decarbonized. The decarbonization prevents the hydrogen produced by corrosion from embrittling the steel at the surface. Where the steel has been treated, it remains ductile and thereby stops any cracking. The consequences of this procedure are not well documented, and the costs of the treatment are in addition to the production costs of the prestressing steel. However, if the surface of the steel can be made to resist embrittlement, then the formation of cracks can be stopped and progressive failure checked.

10. A potentially helpful treatment, which has not yet been applied to prestressing steels, is shot peening. Bombardment of the suface of the prestressing steel with tiny steel pellets has the effect of closing small surface cracks and introducing compressive stresses in the surface of the wire. Closing the surface cracks eliminates locations where SCC is likely to initiate, and the compressive stresses induced by the shot peening reduce surface tensile stresses in the areas where cracks are most likely to form.

11. It is controversial to recommend use of lower final stress levels, because such advice means that additional prestressing wires must be used to satisfy design requirements, and that means additional costs to the structure. However, it has been shown in tests where wires were stressed to different percentages of their ultimate tensile stress while being exposed to various corrosive environments (Tanaka 1976) that the time to failure in the tests increased as the ratio of applied stress to ultimate tensile stress decreased.

Protective Barriers that Can Exclude Corrosive Gases and Liquids

Concrete

12. The concrete surrounding prestressing steel provides one of the best barriers against the ingress of corrosive environments which cause SCC and hydrogen embrittlement, provided that proper care is taken in the design and placement of the concrete to make it a dense, low-permeability material.

Concrete can provide both physical and chemical protection to the steel which inhibits the conditions needed to promote SCC. First of all, the concrete provides a physical barrier by restricting the path of travel of moisture through the concrete to the level of the steel. The measure of this property is the concrete's permeability. At the 1980 International Conference on the Performance of Concrete in the Marine Environment, one of the points emphasized by nearly all of the participants was that the permeability of concrete was one of the main properties responsible for concrete durability, and its ability to protect the steel embedded in it.

13. The permeability of concrete is influenced by a number of conditions, the most important of which is the water-cement ratio of the concrete mixture. When the cement-water paste is initially mixed, a portion of the water used is chemically combined with the cement grains to form hydrated cement crystals and cement gel. The remainder of the water occupies space within the mixture and acts somewhat in a lubricating capacity, in that the greater the amount of uncombined water that is available, the more fluid the fresh paste will be. The volume occupied by this uncombined water forms capillary pore spaces or passageways in the paste as the paste hardens. The important effect on the resulting permeability of the paste, with respect to the water-cement ratio, is that the more water that is mixed with the unhydrated portland cement (the higher the water-cement ratio), the greater is the formation of these capillary pores. These capillary pores are the main channels through which liquids and gases can pass. If there are many of them, the chances that they will link together and form longer paths through which moisture can flow increases. Maintaining a low water-cement ratio keeps the volume of uncombined water to a minimum and reduces the continuity of the network of connected capillary pores. Powers et al. (1954) showed the dramatic increase in permeability with increase in water-cement ratio. From their data for mature cement pastes, graphed in Figure 3, a reduction in water-cement ratio from 0.7 to 0.3 represents a thousandfold decrease in permeability. It is not intended here to recommend a water-cement ratio of 0.3, due to considerations of workability of the mixture, but maintaining the water-cement ratio below 0.55 will keep the permeability of the cement paste at a low rate of penetration. For example, according to the data published by Powers and his associates, a water-cement ratio of 0.55 would give a permeability of 1×10^{-13} m/s, or 0.03 mm/10 years. Quite obviously, concrete will not behave

as effectively as cement paste, and the permeability will be higher due to inclusion of coarse and fine aggregate, entrapped and entrained air, and deficiencies in the compaction of the concrete; however, the data serve to establish the importance of lower water-cement ratios in the concrete.

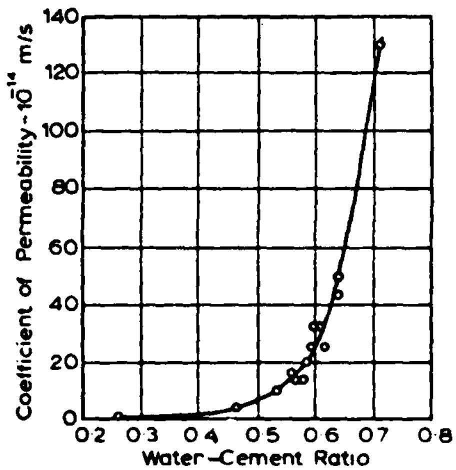


Figure 3. Relationship between permeability and water-cement ratio for mature cement pastes

14. It is important to mention the effects of workability as they affect the resulting permeability. While a very low water-cement ratio decreases the amount of uncombined water, and therefore reduces the volume of capillary pores, this same low water-cement ratio reduces the lubricating effect that the uncombined water imparts to the fresh concrete. An extremely low amount of water used for lubricating the concrete mixture imparts poor workability to the mixture and limits the ability of the cement paste to properly coat all the aggregates and embedded material. This *affects the compaction* of the concrete, which ultimately affects the permeability. This will be discussed more later. Ultimately there should be a compromise between low water-cement ratio and workability which imparts sufficient workability to the mixture to allow the cement paste to flow around all embedded elements as well as to achieve a low permeability of the hardened concrete. This compromise works well at water-content ratios between 0.50 and 0.55 with the use of a well graded-aggregate.

15. The proper choice of aggregate will reduce the permeability of the concrete. Liquids and gases not only permeate through hardened cement paste, they also permeate porous aggregate. If a coarse aggregate is used that is dense, and itself low in permeability, the liquids and gases will be stopped at the surface of the aggregate particle. In order to continue on their inward path, the liquids and gases must go around the aggregate particle. This increases the length of the path of least resistance, and also increases the time it takes the liquid or gas to reach the surface of the steel. The grading of the aggregate also affects the permeability of the concrete. A smooth grading of aggregate particles from fine to coarse provides for dense packing of the particles in the cement matrix. This makes the path that materials must

travel long and frequently interrupted by fine aggregate grains.

16. As mentioned earlier, the care with which concrete is compacted can mean higher or lower permeability of the hardened concrete. Concrete that is poorly compacted contains honeycomb pockets where the cement paste did not completely surround the aggregate particles. These pockets are channels for liquids and gases to penetrate and progress to the level of the steel. They should be avoided, and can be by the care with which the concrete is compacted. Poor compaction results from insufficient vibration of the freshly placed concrete. Proper vibration allows for the dislodging of entrapped air which has been incorporated into the mixture during the placement operation. It frees this entrapped air and allows the paste and aggregate to settle into a dense matrix, free of honeycombing and pockets of air or water. The use of excessively large coarse aggregate particles, or very flat particles, encourages formation of pockets beneath the aggregate if the concrete is poorly compacted. Overcompaction, on the other hand, also increases the permeability of the concrete. Overvibration tends to segregate the cement paste from the aggregate, bringing excess mixing water (referred to as bleed water) to the surface of the concrete. The excess concentration of water at the surface is similar to making the top layer of the concrete of a higher water-cement ratio, thereby encouraging more capillary voids that increase the permeability. Air that has been entrapped rises to the surface upon overcompaction and further increases the permeability.

17. Properly curing the concrete after it has been placed insures a high degree of cement hydration which also decreases the permeability. The porosity of concrete decreases with its increase in age as the cement continues to hydrate. The hydration process produces a cement gel that attempts to fill the spaces between the hydrated cement crystals and the capillary pores where the uncombined water remains. Since the hydrated gel occupies a volume about 2.1 times the volume of unhydrated cement (Neville 1975), it will attempt to block the capillary pores. Since capillary pores are 20 to 100 times more permeable than gel pores (Powers 1958), the liquids and gases are further blocked by the formation of gel in the capillary pores. If poor curing practices are observed or if no curing measures are taken, the free water that is in the capillary pores and available to hydrate the remaining cement grains will evaporate and stop the hydration process, which stops the production of the cement gel. While it is not always practical to wet cure concrete for a

long period of time, the longer it is allowed to cure, the longer it will continue the hydration process, and the lower value of permeability it will achieve. Curing compounds that form a barrier film on the surface of the concrete will retard the loss of moisture from the concrete pores and increase the amount of hydration of the cement grains. Steam curing is also a method of rapidly curing the concrete which gives a high degree of hydration of the cement. In this process, moisture and elevated temperatures are used to produce accelerated hydration, thereby allowing the length of time needed for moist curing to be shortened. It is expensive and sometimes impractical with respect to prestressed concrete, but is also produces concrete with lower permeability.

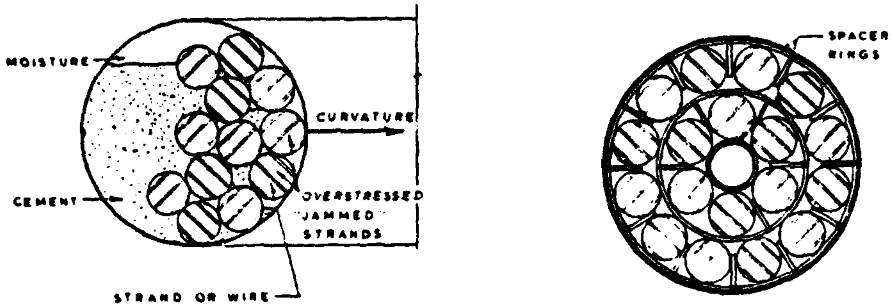
Grouted prestressing systems

18. Posttensioned concrete systems as compared to pretensioned ones require the use of conduit in which to run the stressed wires. The conduit, as well as the grout that is pumped into it after the wires are tensioned, acts as an additional barrier to the ingress of corrosive liquids and gases. Care must be taken in choosing the type of conduit and with the method of grouting the conduit, in order to get the best amount of protection to the tensioned wires.

19. The conduit. Several factors affect the proper choice of conduit. It should not be of the segmental type. Rather, it should be of the continuous type, preferably without a construction seam, in order to most effectively exclude any corrosive environments. The conduit should not be formed of any porous material, such as heavy paper, as this type of conduit rapidly deteriorates. The end anchorages should be so constructed as to give good protection to the wires near where they will transfer their stress from the steel to the concrete, since this is a critical area for SCC problems. Protection of the end anchors is important since the posttensioning system comes in contact with the outside environment at this point. Protective coverings over the anchorage, such as concrete caps, afford an extra measure of protection against liquid or gaseous ingress. Research done by the Waterways Experiment Station (O'Neil 1977) into types of end anchorage protection and methods of attaching these protective coverings yielded some useful results. With respect to the type of end coverage, cap, or recessed plug, it was found that the recessed plug type of covering protects the end anchorage better since there are no joints on horizontal surfaces which trap moisture and become

sites for freezing and thawing damage. Concrete, mortar, and epoxy concrete were tested as materials for the protective coverings. It was found that the epoxy coverings protect best because the permeability of this material is effectively zero. The epoxy mixture used was coarse and fine aggregate bound in an epoxy matrix which replaced the portland cement. The use of epoxy as a joint sealing material between concrete beams and cap type anchorages was tested. This turned out to be a poor method of joining the cap and beam because of the incompatibility of the coefficients of thermal expansion of the two materials. The tests in this research were conducted under field conditions of wetting and drying in seawater and freezing and thawing in severe winter conditions for a period of 12 to 13 years.

20. Grout. The grout used in filling the conduit is the final barrier against the ingress of corrosive liquids and gases. Since the grount is a mixture of portland cement and water, it can have many of the same properties as the cement paste mentioned earlier. Its alkaline nature surrounds the prestressing steel in an environment which does not allow corrosion to take place. It forms a protective oxide film on the steel that seals out any oxygen that may be present to initiate corrosion. The grouting operation to protect these prestressing wires is not an easy task. In order for the grout to be pumped through the conduit and to be reasonably certain to fill the entire cavity, it must be quite fluid. However, as mentioned earlier, high water-cement ratios promote permeable cement paste. Additionally, it cannot be determined whether or not the cavity is being properly filled since the conduit cannot be seen when the grout is being pumped through the sheath. When the wires are tensioned inside the conduit, they have a tendency to bunch together to one side as shown in Figure 4a. This condition makes it more difficult to grout the conduit and insure filling the entire cavity with grout. Grout will not penetrate between the wires where they are jammed together, and pockets of moisture will form where the grout does not reach. It is also important to note that, where the wires are allowed to touch each other or the sides of the conduit, the possibility of crevice corrosion or contact corrosion exists. This condition can be prevented and a situation created that is beneficial to the pumping of the grout around all internal surfaces, if a nonmetallic spacer is used. As shown in Figure 4b, these spacers separate the wires, isolating them from each other and promoting a condition that allows better, more uniform flow of grout within the conduit.



a. Improper grouting and spacing   b. Wires with proper spacing

Figure 4. Sketch of wire spacing

Other protective coatings

21. Galvanizing. Galvanized prestressing wires have caused much controversy in the past 20 years, due to the possibility of hydrogen embrittlement occurring where the protective coating on the steel had been damaged. Much of the research conducted in the past 10 years addressing this problem (Brachet 1977; Moore, Klodt, and Hensen 1970; Netherlands Committee for Concrete Research 1971) has indicated that the hydrogen embrittlement condition should not be a problem. It has the advantage of providing good protection to the steel both in situ and, during the shipping and storage condition, before it is put into the structure, a time when moisture and oxygen can cause harmful corrosion to the steel if it is left unprotected. It is more expensive; however, the added corrosion protection more than offsets the extra cost.

22. Plastic coatings. Epoxies have been proposed as coatings to be applied to the prestressing steel as a barrier against corrosive media, but their success as a coating to the steel has not been totally proven. Painted on epoxy coatings are prone to producing pinholes that can lead to serious corrosion conditions, and their bond to the steel is not as tight as when the epoxy is sprayed on the steel in a powder form and thermally bonded to the steel. The latter method is better than painting in both coverage and bond. It has also been suggested that posttensioning conduits be filled with epoxy rather than portland-cement grout; however, this method is expensive due to the volume of polymer used in the process.

23. Impregnated polymer concrete. As a barrier to liquids and gases, especially corrosive ones, the use of polymers impregnated in the pore structure of the concrete provides a more useful barrier to chemicals that promote

SCC. Polymer impregnated concrete is achieved by soaking monomer into the pore structure of the concrete and then polymerizing it in place by the use of either heat or catalysts that harden the polymer once it is in the concrete pores. Since polymers are impervious to both liquids and gases, and resistant to most acids and alkalies, they provide a good barrier against aggressive media as well as improving the durability of the concrete into which they were introduced.

Summary

24. In summing up this brief review of preventative measures that can be taken to minimize the occurrence of stress corrosion cracking of prestressing steel, several important points should be stressed. While there have been some important strides made in understanding the mechanisms that cause SCC, there remains much that is not known. However, minimizing the chances that SCC will occur is not a serious problem, provided sound judgment is used in selecting an environment for the steel that will eliminate one of the causative conditions of the phenomenon. The proper choice of the steel and the process by which it was produced will minimize chances of SCC by utilizing a material that is resistant to the conditions that promote it. Providing as many barriers against the ingress of corrosive liquids and gases as is possible will keep the environment surrounding the steel as free as possible of the materials that promote SCC. In this respect, concretes and grouts with reasonable, low permeabilities are most effective while being the most economical materials to use. If the practices used in making such concretes are understood, they can be easily produced. And finally, prudent judgment in the amount of prestress force applied to the wire will reduce the chances of SCC by providing an additional factor of safety to the structure.

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